The Growing Imperative and Transformative Impact of Cyber-Physical Systems

Farnam Jahanian

CISE Directorate

National Science Foundation

CPS Week 2011

Chicago, Illinois

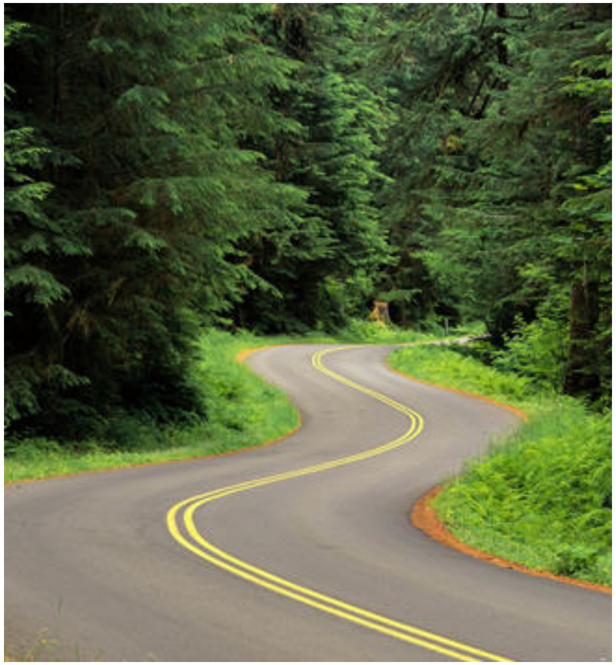
Opening Remarks

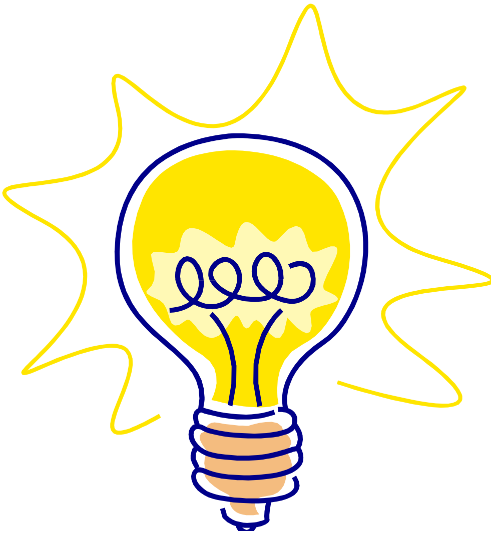
- Growing and thriving CPS community
- Remarkable accomplishment in creating an interdisciplinary community of researchers, practitioners, and policy makers
- Broad participation from academia and growing interest from industry and government
- Impressive international momentum (US, European Community, S. Korea, Taiwan, Japan, …)
- Potential for highly engaged virtual communities

- NSF will continue to support and nurture the CPS community!

Roadmap

- IT Innovation Ecosystem
- Trends and Advances Shaping the Computing Discipline
- IT and National Priorities
- Cyber Physical Systems
- Wrap-up





IT Innovation Ecosystem

What's Ahead?

- Computer and Information Science and Engineering (CISE) is at the center of this ongoing **societal transformation** and will be for decades to come.
- The **explosive growth of scientific and social data**, wireless connectivity at broadband speeds for billions of endpoints – which are both people and environmental sensors – and seamless access to computational resources and applications in the "cloud" are transforming the way we work, learn, play, and communicate.
- The impact of computing will go **deeper into the sciences and engineering** and will become more **pervasive** throughout society. Policy issues will loom larger as our reliance on technology and computationally-enabled collective intelligence grows.

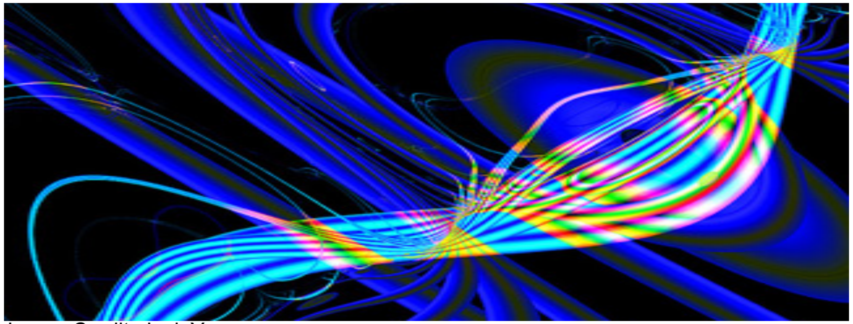


Image Credit: Jack Yaco

Potential for Computing

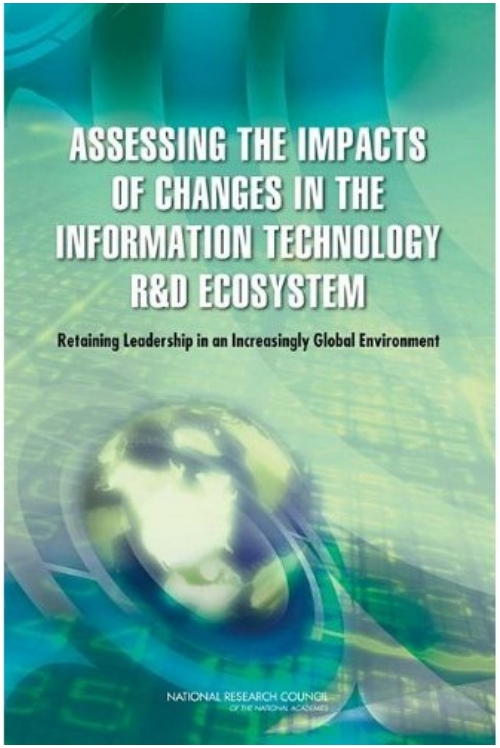
- Computing research and education has the potential to form a pervasive intellectual fabric that connects a wide range of disciplines – recognizing that:
  - Scientific discovery and technological innovations will be **at the core of our response to challenges facing humanity** – from climate change and sustainability, to health care and national security.
  - Many of tomorrow's breakthroughs will occur at **the intersections of diverse disciplines.**

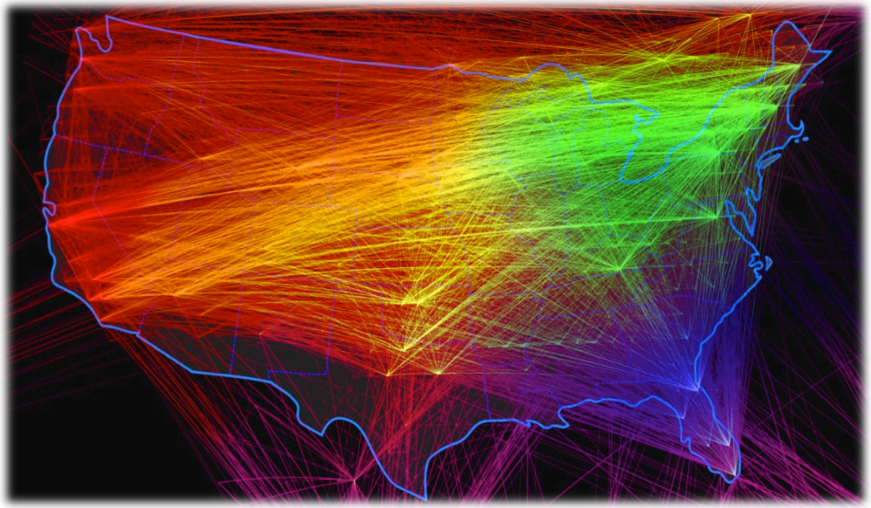
Courtesy of National Institute for Computational Sciences and the University of Tennessee, photo taken by Jason Richards at Oak Ridge National Laboratory


Credit: Kirsty Pargeter

What is the Impact of Information Technology?

- The enormous global economic impact is not only from the growth of IT industry itself, but to a greater extent from IT-enabled productivity gains from across the entire economy.
- Since 1995, Networking & IT industries accounted for 25% of US economic growth.
- The use and production of IT accounted for "roughly 2/3 of the post-1995 step-up in labor productivity growth."
- Most investment in basic research comes from the federal government.





Credit: Map by Zina Deretsky, National Science Foundation, adapted from maps by Chris Harrison, Human-Computer Interaction Institute at Carnegie Mellon University (http://www.chrisharrison.net).

Research, Innovation, Globalization, and Economic Growth

A National Imperative

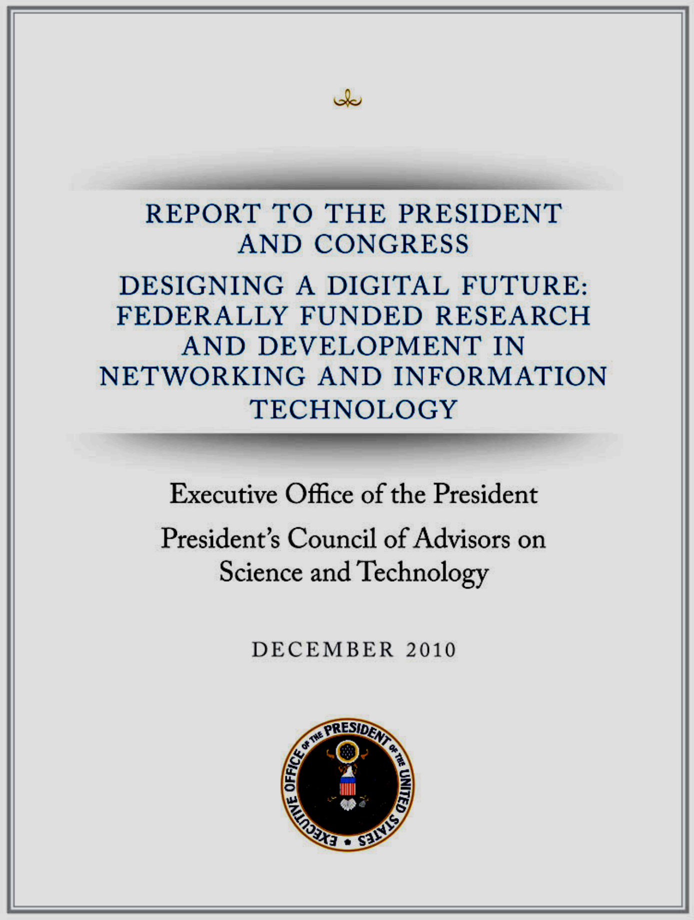
"Recent technological and societal trends place the further advancement and application of NIT squarely at the center of our Nation's ability to achieve essentially all of our priorities and to address essentially all of our challenges."[1] Advances in our discipline:

•are a key driver of economic competitiveness

•are crucial to achieving our major national and global priorities in energy and transportation, education and life-long learning, healthcare, and national and homeland security

•accelerate the pace of discovery in nearly all other science and engineering fields

•are essential to achieving the goals of open government


REPORT TO THE PRESIDENT AND CONGRESS

DESIGNING A DIGITAL FUTURE: FEDERALLY FUNDED RESEARCH AND DEVELOPMENT IN NETWORKING AND INFORMATION TECHNOLOGY

Executive Office of the President

President's Council of Advisors on Science and Technology

DECEMBER 2010

[1] "Designing a Digital Future" PCAST Report – a periodic congressionally-mandated review of the Federal Networking and Information Technology Research and Development (NITRD) Program.

Initiatives to Achieve National and Global Priorities

Call for specific initiatives in NIT focused on several priority areas

- "A national, long-term, multi-agency research initiative on NIT for **health** that goes well beyond the current national program to adopt electronic health records."
- "A national, long-term, multi-agency, multi-faceted research initiative on NIT for **energy and transportation**."
- "A national, long-term, multi-agency research initiative on NIT that assures both the **security** and the **robustness** of cyber-infrastructure."
- Similar initiatives on **education** and **digital democracy**.

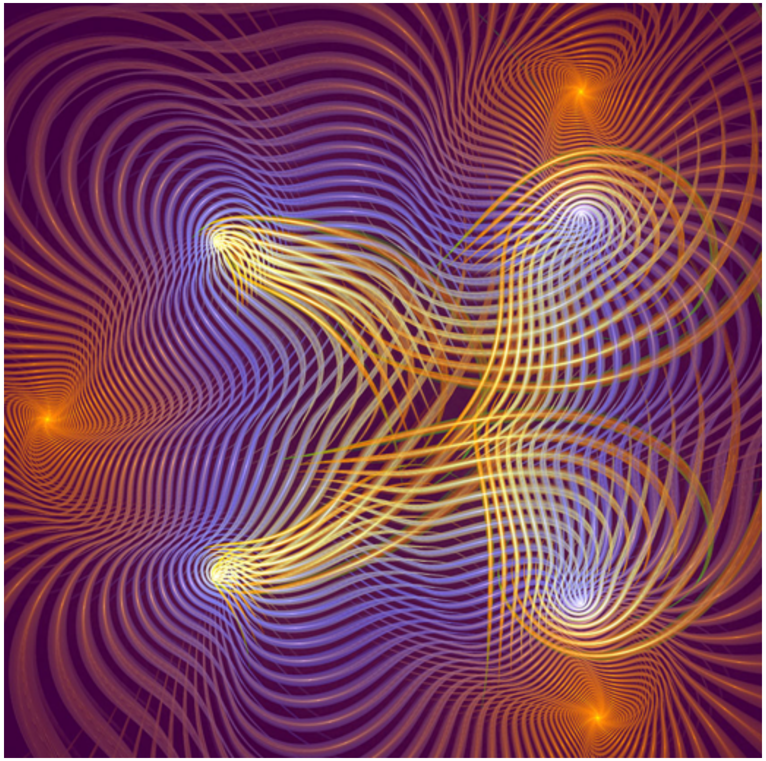
Innovating for Society: The NSF/CISE View

Three Pillars of Innovation Ecosystems

1. Invest in the building blocks of American innovation
2. Catalyze breakthroughs for national priorities, and
3. Promote competitive markets that spur productive entrepreneurship through:
   - Bold experimentation
   - Focus on the frontiers and the unknown
   - Promotion of innovation communities, and
   - Public private partnerships

Image by: Sanwali - roundedoff.com

Trends and Advances Shaping the Computing Discipline

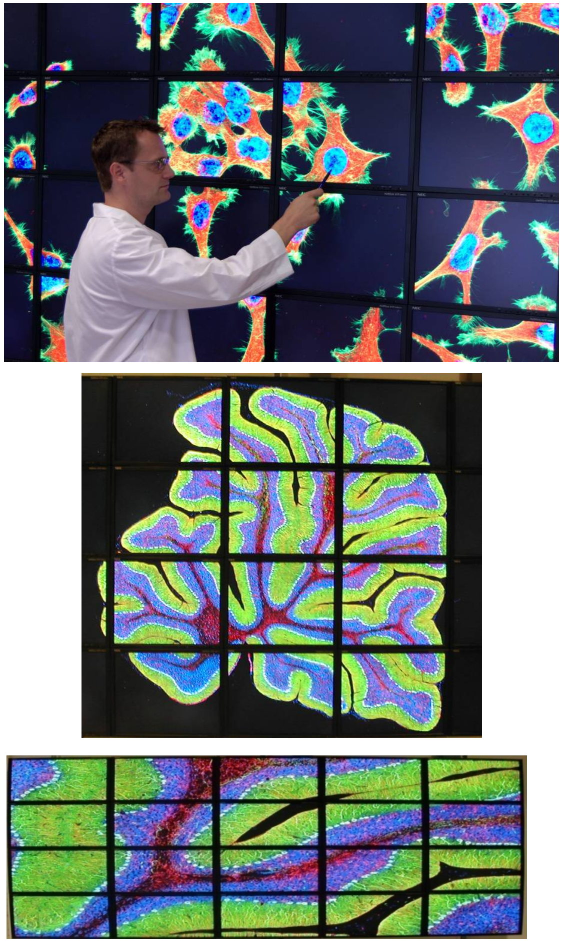


Societal and Technological Trends

- Exponential increase in volume and complexity of data
- Universal connectivity and ubiquity of broadband speeds
- Melding of the cyber world with the physical world
- Explosive growth of mobile devices and distributed low-power sensors
- Emergence of cloud computing paradigm
- Transformation and convergence of communications, media, entertainment, and public discourse
- Emergence of social computing, crowd sourcing and distribution collaboration
- All goes mainstream from machine learning, robotics and speech recognition to augmenting human capabilities
- Transformation of commerce and acceleration of globalization
- Rise politically- and economically-motivated cyber-crime

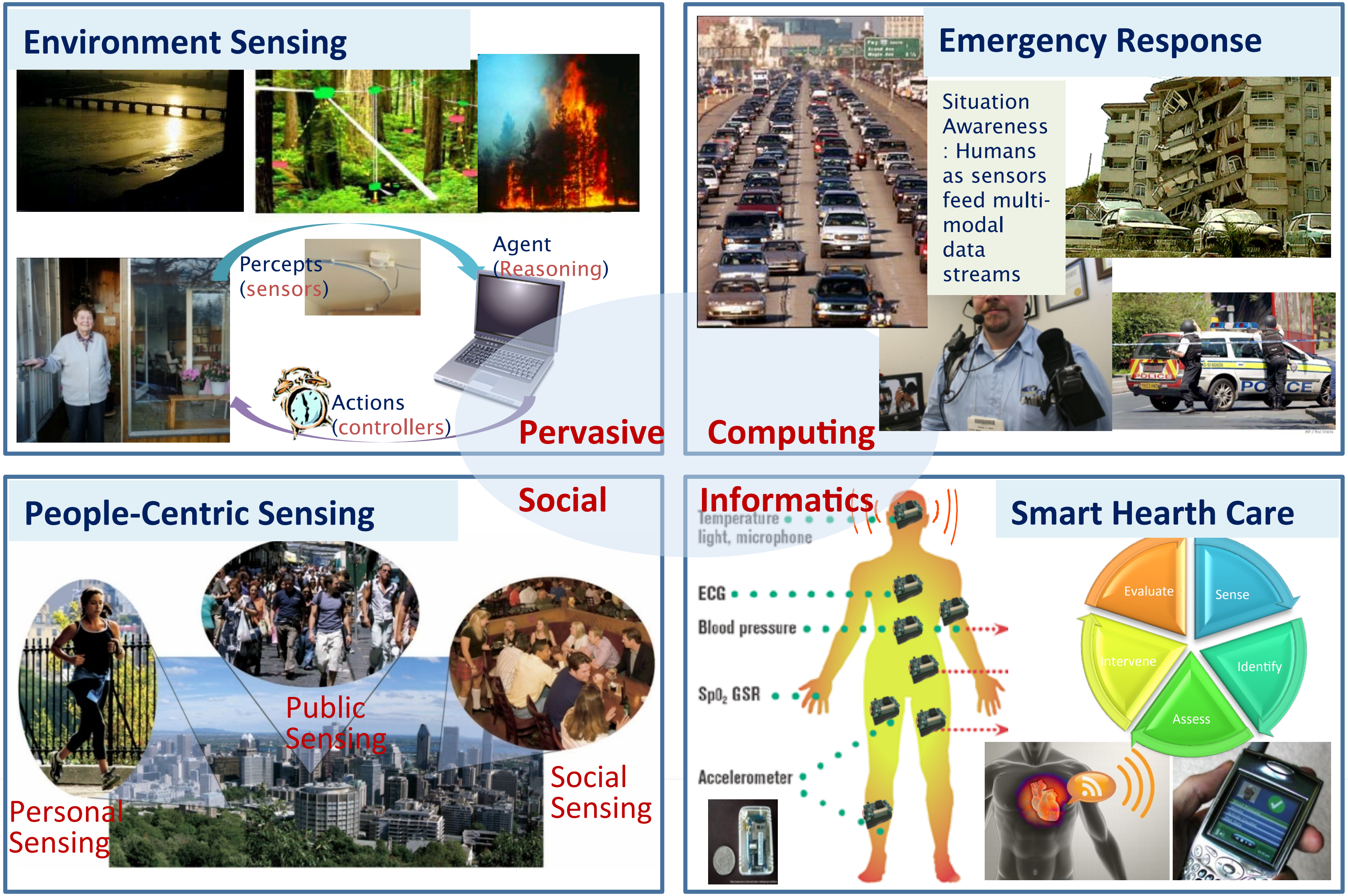
Explosive Growth in Size, Complexity and Data Rates

- **Enormous static or streaming data sets** generated by modern experimental and observational methods
- **Infusion of computation into science and engineering** is revolutionizing research
- Shift toward indirect, **automatic extraction of new knowledge** about the physical or biological world continues to accelerate
- **Enabled by data mining and machine learning**, discovery and visualization techniques together with the emergence of multi-core processing and advanced server architectures



High Resolution Portals to Global Science Data: Multi-Scale Biomedical Imaging from Cerebellum to Individual Neurons. Credit: Mark Ellisman and Tom Deerinck, NCMIR/UCSD

The Age of Observation: Smart Sensing, Reasoning and Decision



Source: Sajal Das, Keith Marzullo

Credit: Image courtesy of University of Florida

New Breed of Communications

1988

Remarkable
Pace of innovation

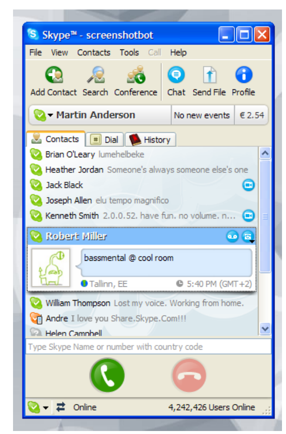
2010

IM

BLOGS

MOBILE

EMAIL



VOIP

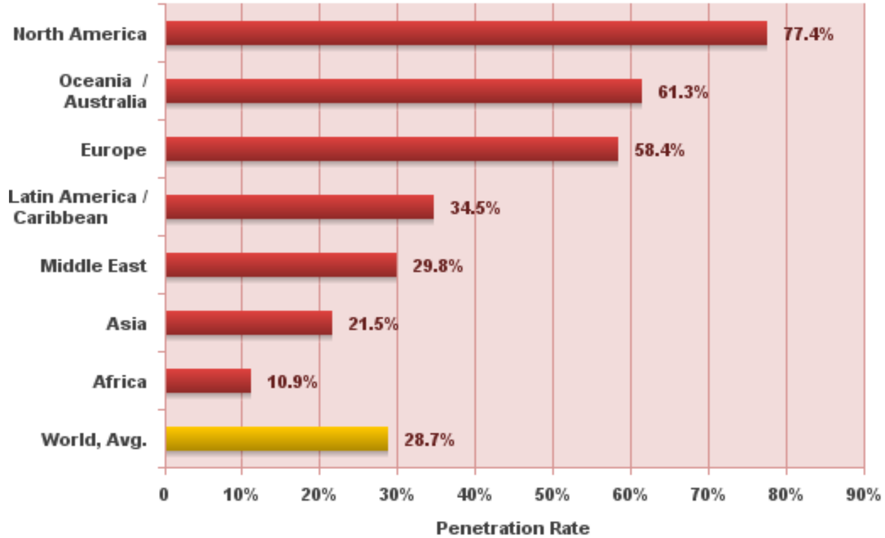
VIDEO

Explosive Growth in Volume & Traffic Diversity

VoIP	663M registered Skype users in March 2011. Represents 20% of long distance minutes world-wide. If Skype were a carrier, it would be the 3rd largest in the world (behind China Mobile and Vodaphone). Largest provider of cross-border communication.
Video	Recent estimates as high as 60% of internet traffic is video and music sharing via P2P; 35 hours of new videos are uploaded every minute in 2011; 2 billion views per day.
Twitter	Currently 175 million registered users.
Broadband	20% of global internet users have residential broadband; 68% in US subscribe to broadband.
Mobile	5.3 billion mobile phone subscribers; 85% of new handsets will be able to access the mobile web; 1 in 5 has access to fast service, 3G or better; IM, MMS, SMS expected to exceed 10 trillion message by 2013; 300K new mobile applications in 3 years.

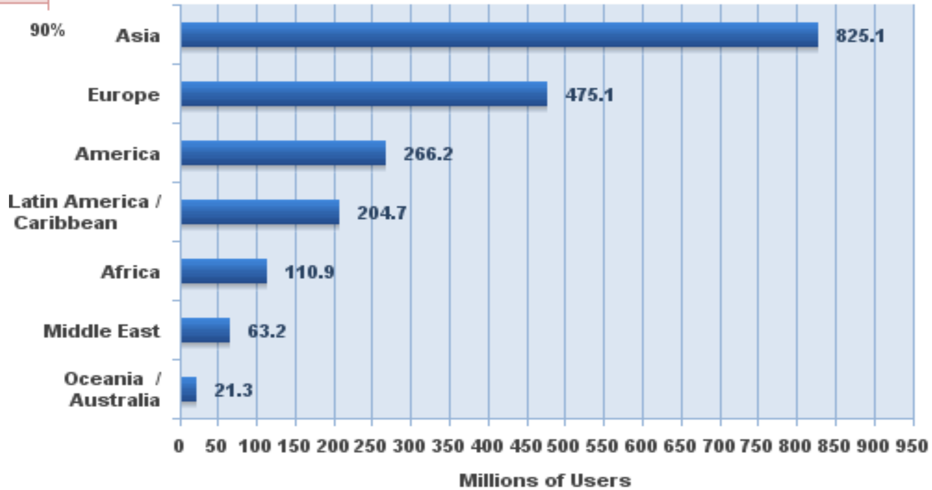
Will the Growth Slow Down?

World Internet Penetration Rates
by Geographic Regions - 2010



Source: Internet World Stats - www.internetworldststs.com/stats.htm
Penetration Rates are based on a world population of 6,845,609,960
and 1,966,514,816 estimated Internet users on June 30, 2010.

Internet Users in the World
by Geographic Regions - 2010



Source: Internet World Stats - www.internetworldstats.com/stats.htm
Estimated Internet users are 1,966,514,816 on June 31, 2010

From the PC Age to the Utility Age

- The idea of providing computing power, like electric power, over a network grid from large-scale utilities has been around for 40+ yrs:
  - Time-share system in 70s
  - ADP's computing jobs as fee-for-service in 80s
  - Grid computing and supercomputing centers
  - Application service providers (ASP), thin clients, and software-as-a-service in 90s

Credit: Courtesy Pittsburgh Supercomputing Center

- The underlying concept goes back to the 1960s:
  - "Computation may someday be organized as a public utility." [John McCarthy]

The Era of Cloud Computing

- Major public cloud service providers like Amazon are now able to provide vast computing resources to organizations … the interest in such services is staggering.
- Each day Amazon adds enough computing resources to power one whole Amazon.com circa 2000.
- Gartner Inc. believes the cloud computing market place will grow substantially from about $60B in 2010 to $149 billion by 2014.
- A whole generation of Internet companies wouldn't be here today without the cloud: Netflix's video-on-demand service runs on it; Zynga uses it to handle spikes.
- The one constant in computing has been the explosion of data. The cloud is making data analytics available to small companies; a technology that was once available only to the largest companies in the world.
- Everybody is planning in this arena:
  - On one side you have: Amazon, Google, Microsoft, and salesforce.com
  - On the other hand, you have all the traditional software and hardware infrastructure companies:

    IBM, HP, Cisco, Juniper, EMC/VMWare, Dell, AT&T and Verizon

Challenges and Opportunities

- Programming parallel applications with hundreds of threads – need for new programming abstractions and tools for software synthesis and dynamic analysis
- Placement strategies and load balancing algorithms
- Architectures, systems, network support: Can clouds become as reliable as the power grid? Achieving 99.999% uptime?
  - Gmail multi-hour outage in 2009
  - Amazon Web Services failure in 2008
  - Rackspace massive outage in 2007
  - Application failover
- "Greener" more environmentally sensitive solutions
- Workload-aware and energy-aware approaches to power, cooling, traffic and server management
- Cloud security and privacy: emergence of new threats and managing risks
- New ways to meter and set prices for services (economic models); from most to least cost

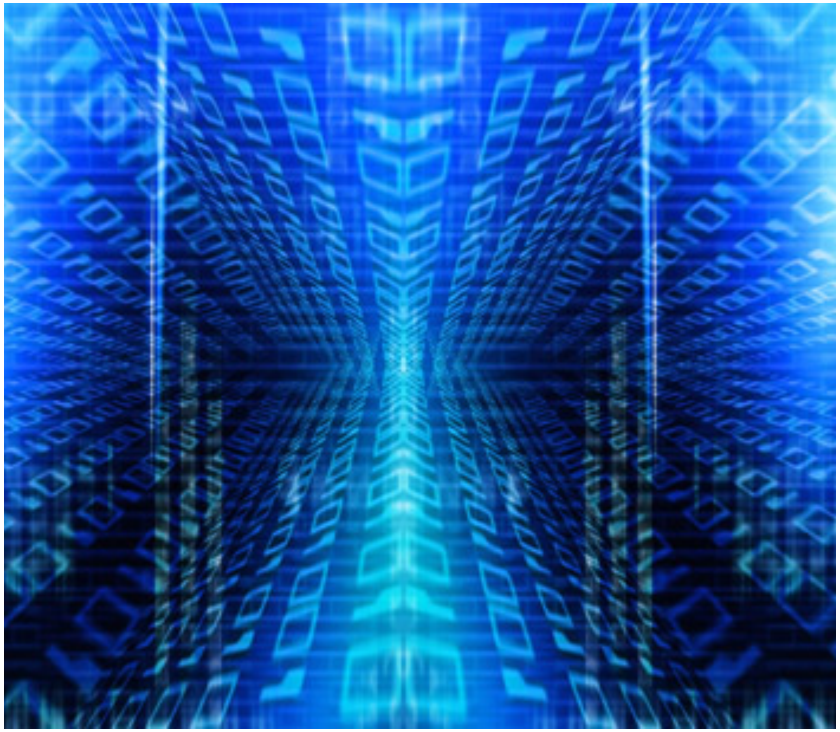
Credit: Wifinotes

Least expensive city for data centers = Sioux Falls, SD

Networked Society

Clickworkers
Collaborative Filtering
Collaborative Intelligence
Collective Intelligence
Computer Assisted Proof
Crowdsourcing
eSociety
Genius in the Crowd
Human-Based Computation
Participatory Journalism
Pro-Am Collaboration
Recommender Systems
Reputation Systems
Social Commerce
Social Computing
Social Technology
Swarm Intelligence
Wikinomics
Wisdom of the Crowds

IT and National Priorities



National Priorities

- Smart Health
- Energy and Sustainability
- Trustworthy Computing
- National Robotics Initiative
- Cyber Physical Systems

Smart Health and the Healthcare Crisis

- Some troubling statistics:
  - The cost of healthcare in the U.S. is the highest in the world (per capita, % GDP)
  - The U.S. ranked 37th in the 2000 WHO study of healthcare system performance (8 underlying measures)
  - 50% Americans have 1 or more chronic diseases; age of onset getting younger
  - 98,000 deaths per year due to medical errors
  - 3 lifestyle behaviors (poor diet, lack of exercise, smoking) cause est. 1/3rd of US deaths
  - Current individual medical records have an error rate of 20%

Example Challenge We Can Meet

Aging independently in place:

Move ¼ of institutional care to the home in 10 years

Computational enablers:

- Medication reminders
- Exercise / therapy coaches
- Medical instrument preparation monitor
- Activity and behavioral monitoring
- Robust intra-family communication
- Social networking
- Fall detector
- Robotic lifter
- …

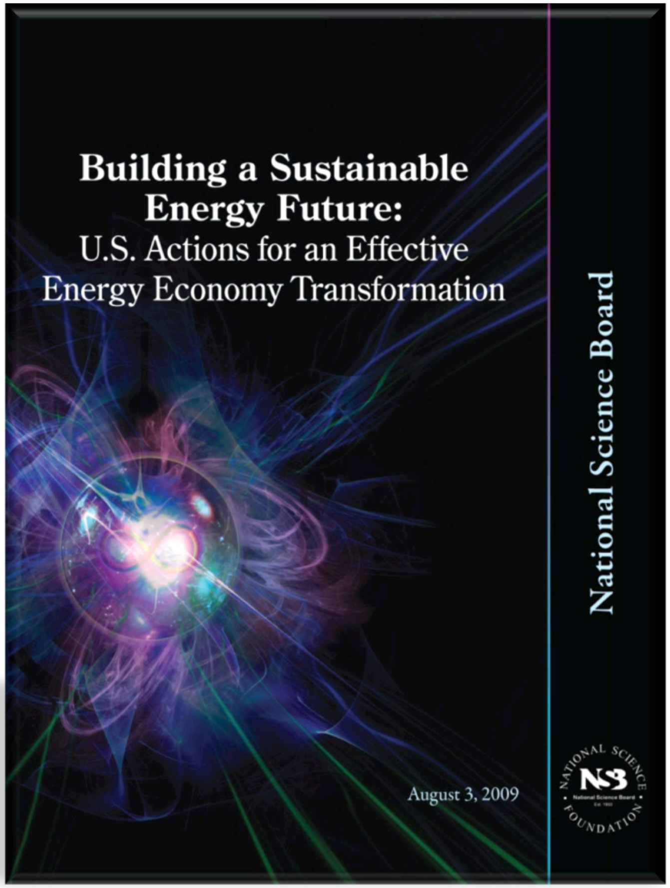
Smart Health and Well Being Thrusts

- A Learning Health System – ***Informatics and Infrastructure***
  - Continuous accrual and integration of EHR, pharma and clinical research data in a distributed but federated system
  - A foundation for evidence-based, patient-centric practice & research
- Data to Knowledge to Decision – ***Reasoning under uncertainty***
  - Cognitive support systems spanning clinical to lay decision making
  - Data mining, machine learning, discovery from massive longitudinal and individual genomic data
- Empowered "e-patient" – ***Energized, enabled, educated***
  - New models of distributed and home-centered healthcare provision
  - Technologies that aide in modifying self and group behavior
- Cyber-physical healthcare systems – ***Sensor-based actuation***
  - Assistive technologies embodying computational intelligence
    - Medical devices, co-robots, cognitive orthotics, rehab coaches

Science, Engineering, and Education for Sustainability (SEES)

Achieving a sustainable human future in the face of both gradual and abrupt environmental change is one of the most significant challenges facing humanity.

Generating discoveries and building capacity to achieve an environmentally and economically sustainable future.

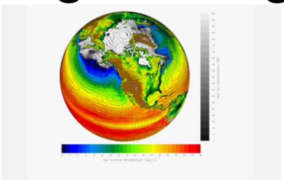


Science, Engineering, and Education for Sustainability (SEES)

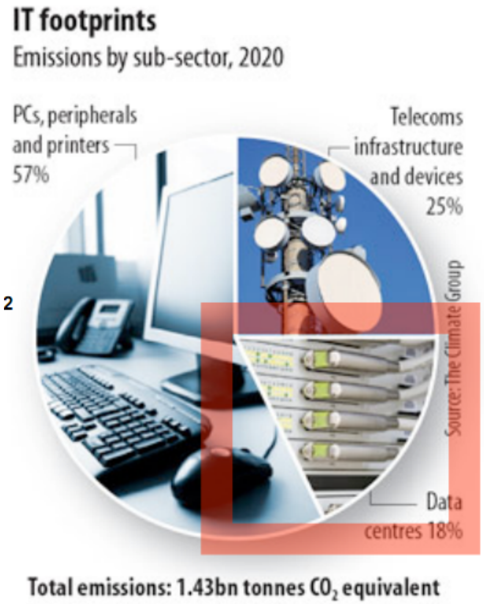
- IT as a consumer of energy
  - 2% (and growing) of world-wide energy use due to IT
- IT as a helper, especially for the other 98%
  - Direct: reduce energy use, recycle, repurpose, …
  - Indirect: e-commerce, e-collaboration, telework -> reduce travel, …
  - Systemic: computational models of climate, species, … -> inform science and inform policy
- Engages the entire CISE community
  - Modeling, simulation, algorithms
  - Energy-aware computing
  - Science of power management
  - Sensors and sensor nets
  - Intelligent decision-making
  - Energy: A new measure of algorithmic complexity and system performance, along with time and space

SEES and CISE

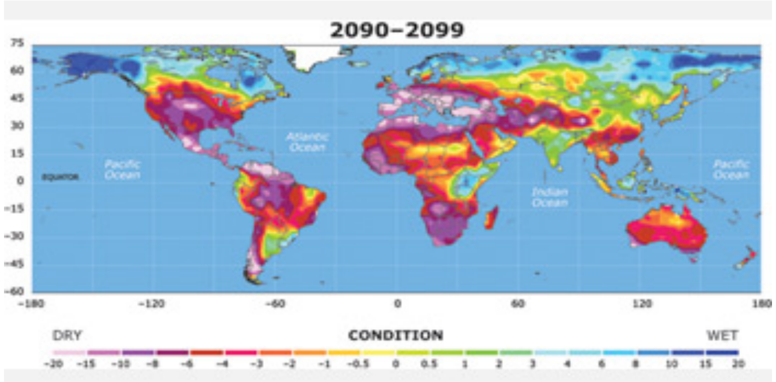
Interdisciplinary research in the areas of environmental & energy science and engineering



Credit: Gary Strand, NCAR



Credit: Climate Group and Molly Webb

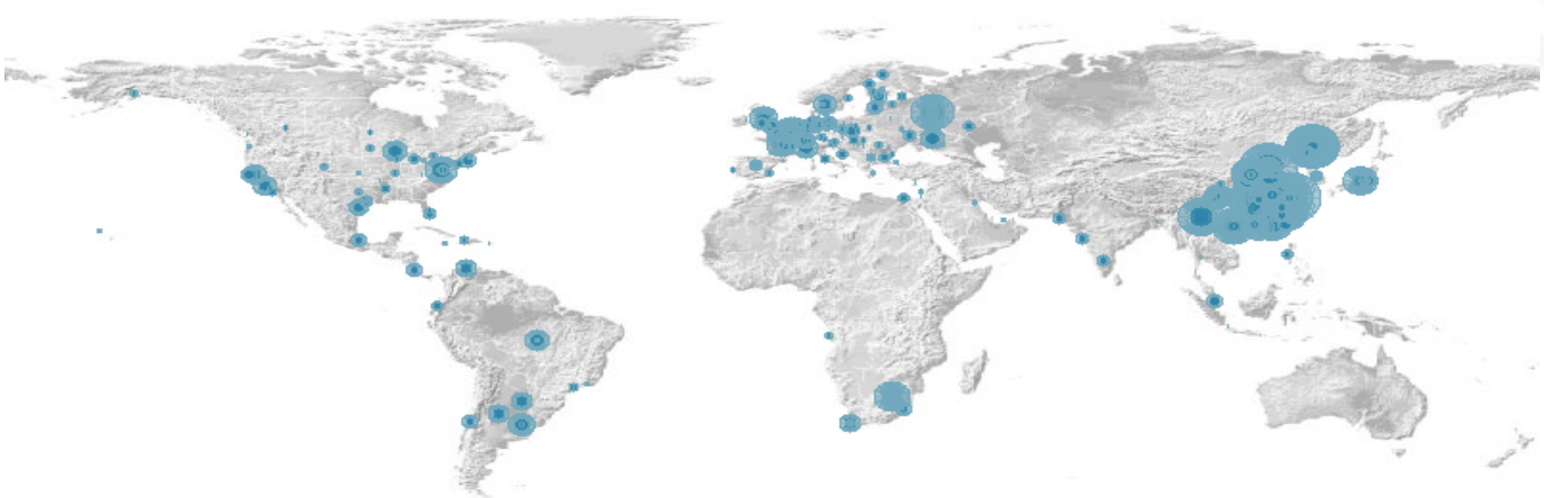


Disciplinary research to develop the foundation of energy-efficient, energy-aware, and sustainable computing and communication

Credit: (c)UNEP

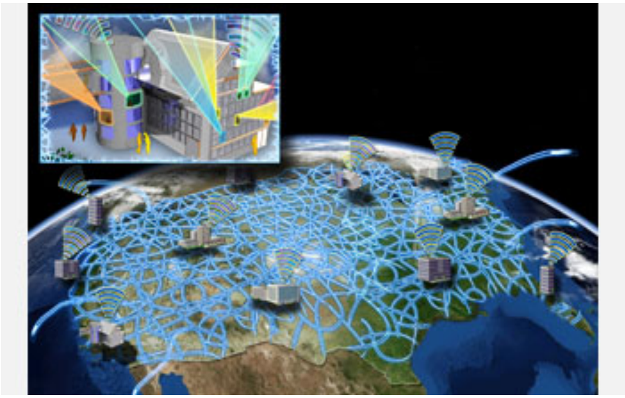
A World of Cyber Threats

- DDoS attacks
- Worms
- Trojan Horses
- Spyware
- Botnets
- Phishing
- Insider misuse
- Data theft



Cyber Threats: 2011 and Beyond

Future security challenges will follow Internet adoption patterns:



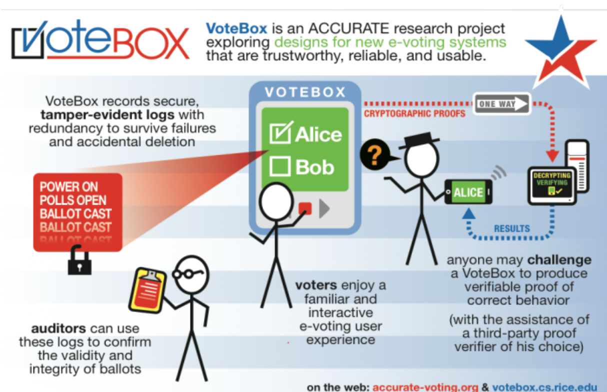
Credit: Nicolle Rager Fuller, National Science Foundation

- Proliferation of attacks spurred by financial gains and now political motives.
- Cyber-networks are the new frontier of counterintelligence.
- Distributed attacks increasing in size and sophistication, targeting specific applications.
- Botnets will continue to dominate how attacks are launched; attribution will become increasingly difficult.
- Proliferation of wireless devices and social media platforms open new avenues for hackers and bring evolving security challenges.
- Protecting cloud infrastructure key to long-term adoption.

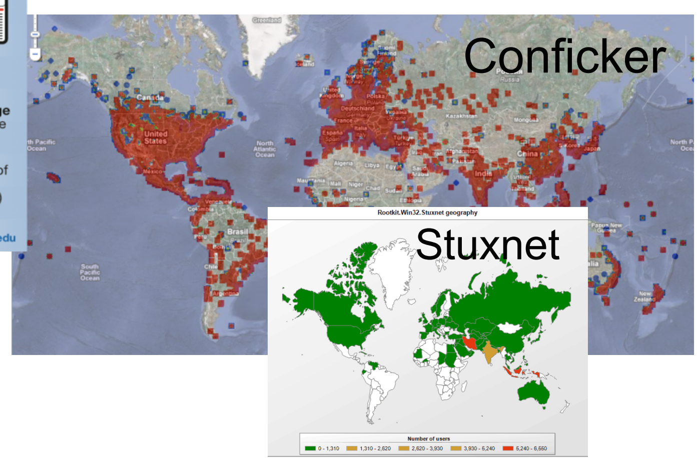
Trustworthy Computing Across CISE

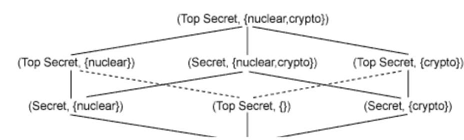
Systems projects and center scale activities addressing voting, future power grid, electronic health records, automotive systems, and more.

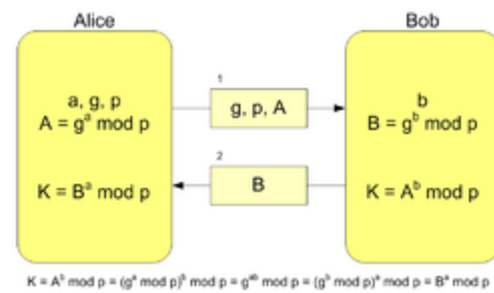
Disciplinary projects advancing theory, design, implementation, test, verification, detection, response, hardware and software, human and economic aspects.



Computing in the presence of an adversary.



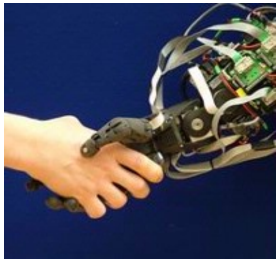




Over 500 active awards, nearly 400 projects

The National Robotics Initiative

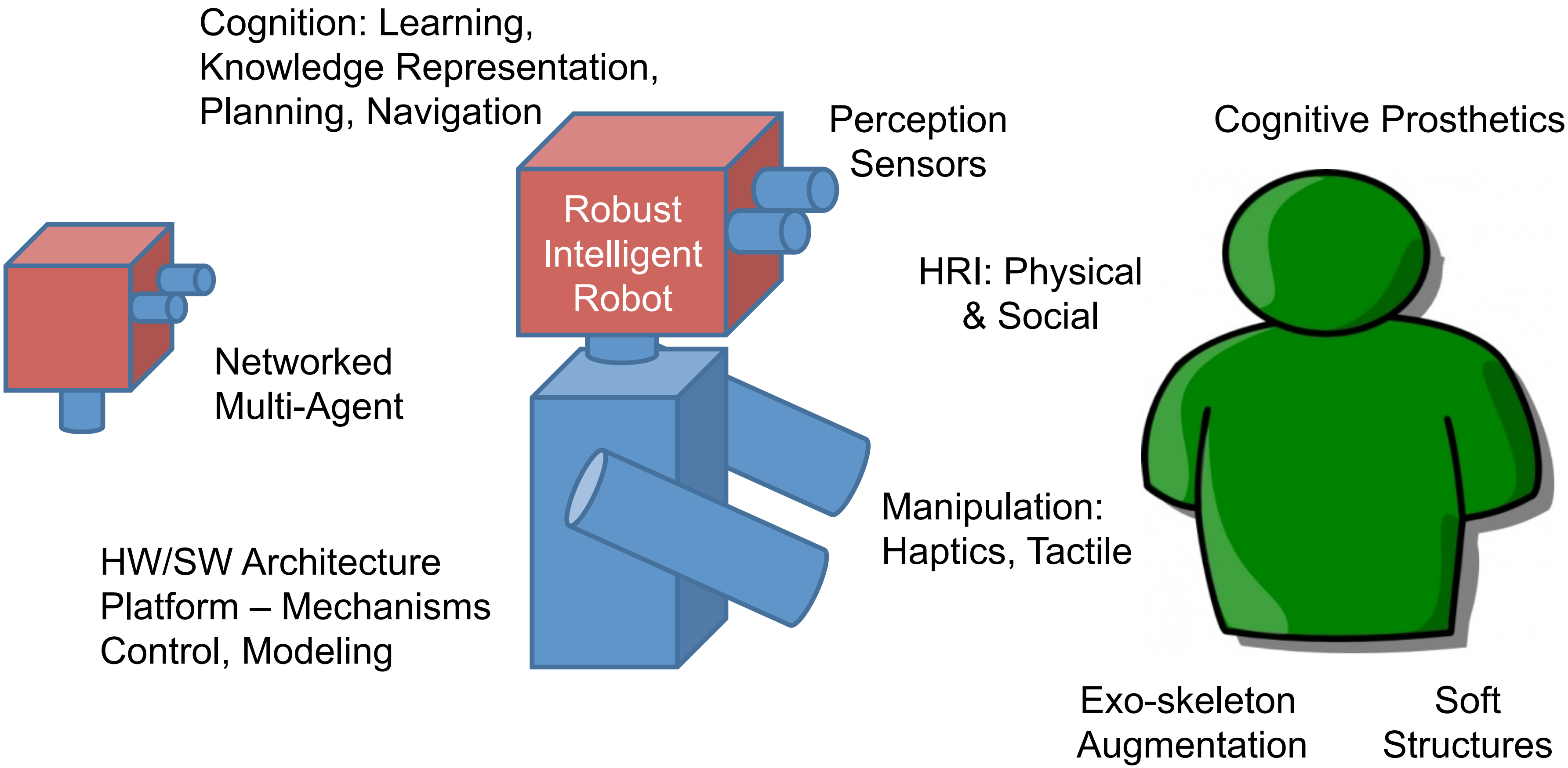
- Definitive report on challenges and opportunities: *"A Roadmap for US Robotics- From Internet to Robotics," May 21, 2009*. http://www.us-robotics.us/reports/CCC Report.pdf
- A nationally coordinated robotics technology R&D program across multiple government agencies
  - Joint solicitation being developed by NSF CISE, ENG & SBE
  - Multi-agency commitment
- Serves multiple national priorities including increased productivity in manufacturing, healthcare, and security
- Strong coupling with industry and startups, through SBIRs
- Will sponsor national competitions, outreach, and education



Credit: Photo Permission by Bristol Robotics Lab

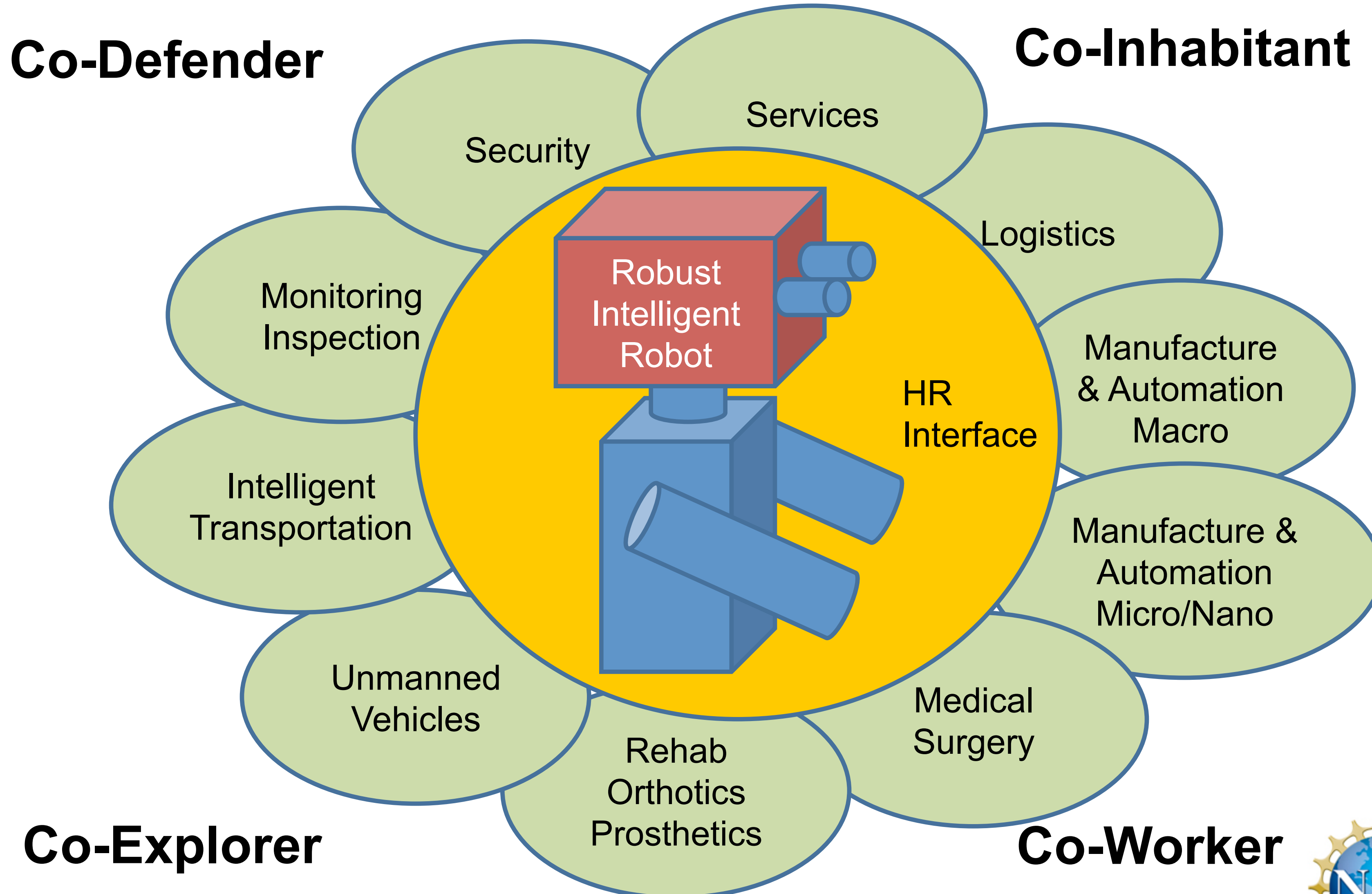
Credit: 2011 Honda Motor Co., Ltd.

NRI: The Technology Space



Mobility: legged, wheeled, aquatic, aerial

NRI: The Technology Space



Why Was the CPS Program Created?

National Priorities and Trends in Computing outlined in several reports[1] include: health, wellbeing, and medicine; high-confidence critical infrastructures; safer transportation systems; collaborative intelligence; competitive economy and our manufacturing base; our aging population; ... networked information systems connected to our physical world.

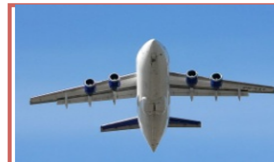
Transportation	• Faster and safer aircraft • Improved use of airspace • Safer, more efficient cars	
Energy and Industrial Automation	• Homes and offices that are more energy efficient and cheaper to operate • Distributed micro-generation for the grid	
Healthcare and Biomedical	• Increased use of effective in-home care • More capable devices for diagnosis • New internal and external prosthetics	
Critical Infrastructure	• More reliable power grid • Highways that allow denser traffic with increased safety	

Photo Courtesy of JeffersonDavid via Flickr

[1] See, for example, PCAST Reports: Leadership Under Challenge: Information Technology R&D in a Competitive World (August 2007) -- http://www.nitrd.gov/Pcast/reports/PCAST-NIT-FINAL.pdf; *Federal Plan for Advanced Networking Research and Development (September 2008) --* http://www.nitrd.gov/pubs/ITFAN-FINAL.pdf; *Grand Challenges: Science, Engineering, and Societal Advances, Requiring Networking and Information Technology Research and Development (Third Printing - November 2006) --* http://www.nitrd.gov/pubs/200311_grand_challenges.pdf

Infrastructure and Sustainability

Envision a day when…

- Static infrastructures such buildings and factories are transformed into smart spaces that adapt to consumption, growth, and changing environmental needs through the use of networked instrumentation and software control.

Kindly donated by Stewart Johnston

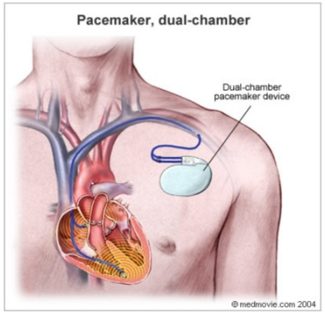
Credit: MO Dept. of Transportation

Smart Health

Envision a day when…

- We can improve quality of life through personalized healthcare and assistive technologies, enabled in part by robust, usable, and trustworthy wearable mobile devices integrated with instrumented environments.

- We can create a healthcare system that helps people prevent and manage chronic and acute diseases in their own every day context; Robots extend independent living for seniors; and devices worn or embedded in the home can report adverse health events.

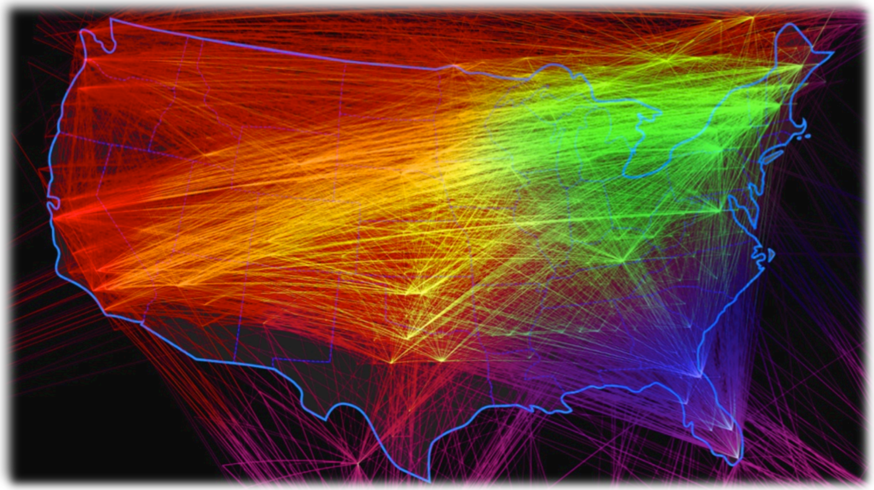


Courtesy of the Center for Integration of Medicine and Innovative Technology (CIMIT)

Smart Grids

Envision a day when…

- Future power grids will be increasingly heterogeneous in energy sources and their locations, and will be efficiently managed through the deployment of intelligent sensor networks and distributed control and decision capabilities – improved quality of transmission, better resource utilization, reduced congestion, and real-time response and real-time pricing.



Credit: Map by Zina Deretsky, National Science Foundation, adapted from maps by Chris Harrison, Human-Computer Interaction Institute at Carnegie Mellon University (http://www.chrisharrison.net).

Emergency Response

Envision a day when…

- During the time of a natural disaster or a national emergency, ***unmanned*** search, rescue and recovery is a reality through the use of autonomous, highly coordinated, and remotely operated robots in shared physical spaces – the promise of distributed, low-power sensing combined with communications and control.

Credit: Edwin Olsen, University of Michigan

Transportation: Safety and Energy

Envision a day when…

- Your car will be able to drive you safely and securely to your destination, where traffic fatalities are uncommon rather than daily events.

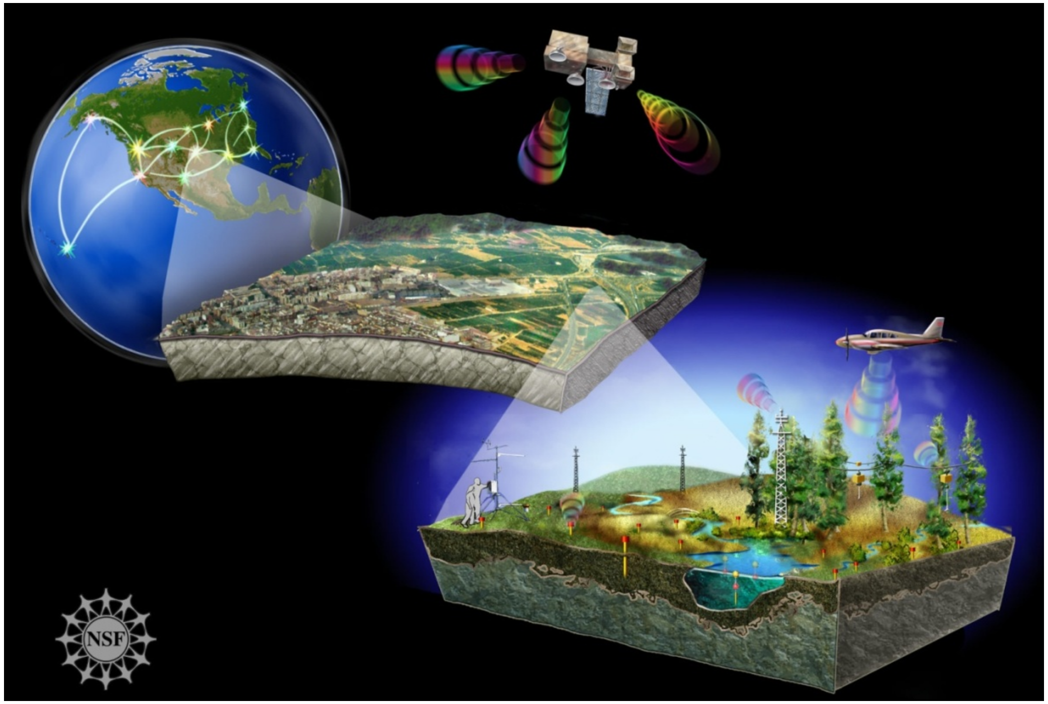
- Your home and car both consume energy from – and provide energy to – the electricity grid, and where advanced controls can provide substantial energy savings that can decouple the economic benefits of transportation from regional and global environmental impacts.

Credit: PaulStamatiou.com

Environment and Sustainability

Envision a day when…

- By developing rich ecological and environmental monitoring systems, we can create accurate models that support forecasting and management of increasingly stressed watersheds and ecosystems.



Credit: Nicolle Rager Fuller, National Science Foundation

The Promise

Advances in CPS hold the potential to reshape our world with more responsive, precise, and efficient systems that:

- augment human capabilities
- work in dangerous or inaccessible environments
- provide large-scale, distributed coordination
- enhance societal well-being

What Do We Hope to Achieve?

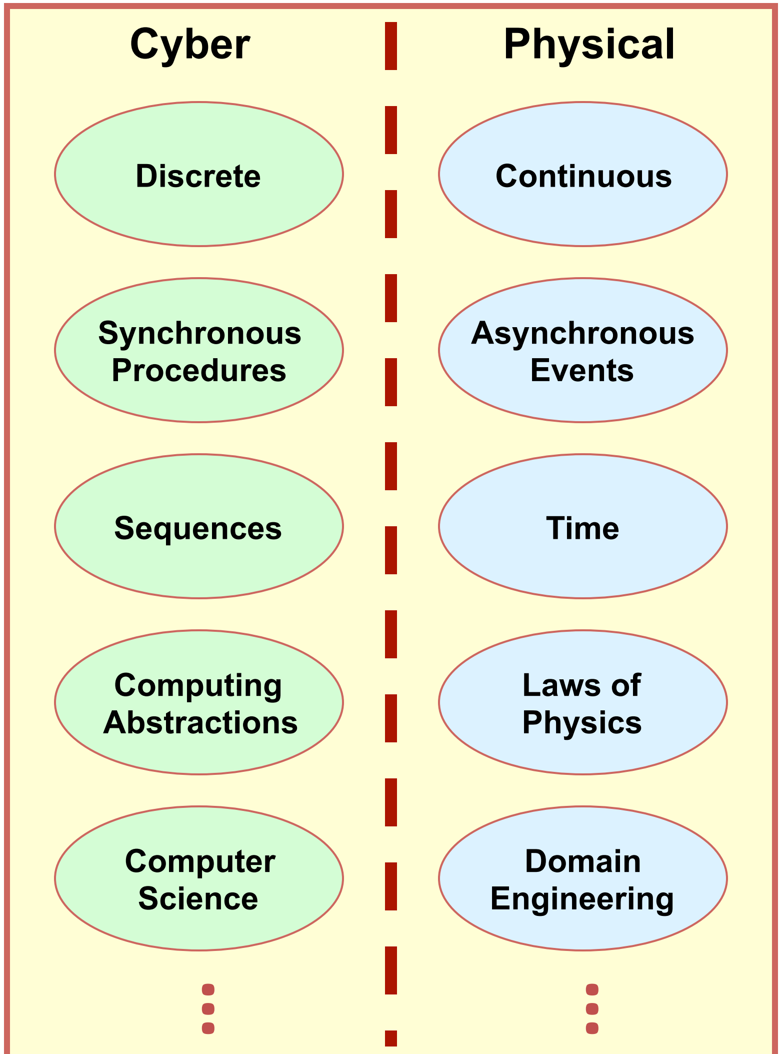
- Enable societal acceptance and reliance – CPS people can bet their lives on
- Overcome complex technical challenges – systems that interface the cyber and physical, with predictable behavior and reconfigurable software and hardware
- *Design for certifiably* of dependable control of (complex) systems
- Discover principles for bridging control, communications, real-time systems, safety, security
- Define next generation system architectures and assurance technology including formal methods and computational frameworks for the design and implementation of reliable, robust, safe, scalable, secure, stable, and certifiably dependable systems
- Develop science and technology for building cyber-physical systems: unified foundations, models, and tools
- Advance cyber-enabled discovery and innovation to enhance understanding and management of complex systems
- Integrate CPS research and education – prepare next generation of practitioners

Enable a research community and workforce that will be prepared to address the challenges of next generation systems

Bridge previously separated areas of research to develop a unified systems science for cyber-physical systems

Develop new educational strategies for a 21st century CPS workforce that is conversant in both cyber and physical aspects of systems

CPS Research Gaps



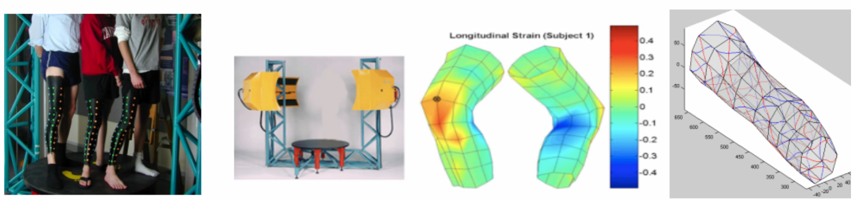
Research Gaps

- Composition
- Design automation
- System integration
- Certification
- Security and privacy
- Education and work force

Examples of CPS Awards

Programmable Second Skin to Re-educate Injured Nervous Systems

Eugene C. Goldfield (Harvard Medical School, Children's Hospital Corp), Rob Wood and Radhika Nagpal (Harvard University), Dava Newman (MIT), Marc Weinberg (Draper), Kenneth Holt and Elliot Saltzman (BU)



Credit: Wyss Institute, Harvard University

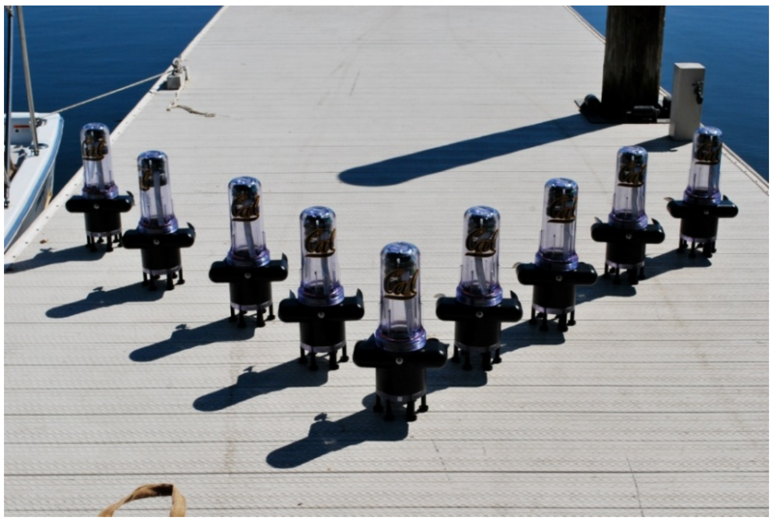
Control of Surgical Robots: Network Layer to Tissue Contact

Blake Hannaford, Howard J Chizeck (U Washington)

Credit: Mitch Lum

Physical Modeling and Software Synthesis for Self-Reconfigurable Sensors in River Environments

Jonathan Sprinkle (U. Arizona), Sonia Martinez (UCSD), Alex Bayen (UC Berkeley)



Credit: Jonathan Beard

Charge to the CPS Community

- The community needs a **research pipeline** (portfolio) comprising of long-term basic research, experimental applied research, prototyping and early deployment, and translation to practical applications.
- Focus on innovating in **core science and technology** for CPS
  – Break down area boundaries: computing, wired and wireless networking/communication, sensing, control, formal methods, security
  – Pay special attention to foundational problems that bridge applications
  – Propose ideas for innovative technology substrates
- We swim in **a sea of sensors** and drowning in data:
  – Our smart phones, cars, increasingly instrumented homes and offices, health monitors, environmental monitors, …
  – New vision and speech recognition techniques for capturing data
  – Ability to Analyze data in "real-time and retrospectively," create context for decisions, and offer meaningful actionable feedback
  – Data fusion and inference techniques over diverse potentially noisy data combined with contextual and location-aware data

Charge to the CPS Community

- As the PCAST report highlights, we need networked systems that not only scale up, but also **scale down and scale out**:
  - Smart, miniaturized, low-power, adaptive, and self-calibrating instrumentation
  - Embedding sensors everywhere and connecting everything via networks leading to wide-scale sensors and control
  - Many of tomorrow's breakthroughs will occur at **the intersections of diverse disciplines.**
  - Invest in multi-disciplinary interactions and collaborations
  - Increasingly important role for Industry partnerships
- Beyond NSF:
  - Engagement from other agencies
  - Coordination with other countries
- Take advantage of the **CPS Virtual Organization**
  - Role of CPS Virtual Organization? sector-based? cross-pollination?
  - Special Interest Groups and Open Source groups
- Look for National Robotics Initiative
- (Awardees) Bring your best ideas and results to the 2011 NSF Grantees meeting – August 1-2, Arlington, VA

Wrap-Up

Community Engagement!

- Volunteer to be a reviewer
- Visit NSF, get to know your program(s) and program director(s)
- Develop transformational ideas and send your best ideas to NSF
- Participate in NSF-funded and hosted activities, e.g., workshops, COVs, ACs, etc.
- Participate in the CCC/CRA visioning activities
- Develop transitional ideas for how to move from ideas and prototypes to systems deployed on testbeds to technology transfer
- Work within your institution to support and reward interdisciplinary research
- Work within your institution to support service to the larger computing community around the globe
- Send us your accomplishments; advertise your research to other citizens through local radio or TV, blogs, newspaper articles, etc.

Thanks!

fjahania@nsf.gov

Credits